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## CHIRALLY SYMMETRIC BUT CONFINED HADRONS AT FINITE DENSITY

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At a critical finite chemical potential and low temperature QCD undergoes the chiral restoration phase transition. The folklore tradition is that simultaneously hadrons are deconfined and there appears the quark matter. We demonstrate that it is possible to have confined but chirally symmetric hadrons at a finite chemical potential and hence beyond the chiral restoration point at a finite chemical potential and low temperature there could exist a chirally symmetric matter consisting of chirally symmetric but confined hadrons. If it does happen in QCD, then the QCD phase diagram should be reconsidered with obvious implications for heavy ion programs and astrophysics.

*Keywords:* QCD phase diagram; chiral symmetry; confinement.

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**1. Introduction.** It is generally believed that chiral and deconfinement phase transitions in QCD coincide and hence beyond the semi-circle in the  $T - \mu$  plane one obtains a deconfining and chirally restored matter. At zero temperature and density the 't Hooft anomaly matching conditions require that in the confining phase chiral symmetry must be broken in the vacuum. However, there is no such a restriction at a finite chemical potential. Typically models that give us information about the phase structure in QCD are of the Nambu and Jona-Lasinio type. These models are not confining, however, and consequently there is no basis to conclude that above the chiral restoration point at finite chemical potential one obtains a chirally symmetric and deconfining quark matter.

Recently McLerran and Pisarski presented qualitative large  $N_c$  arguments showing that at reasonably large chemical potential and low temperature there might exist a confining but chirally symmetric phase<sup>1</sup>. This suggestion is in conflict with the naive intuition that once the hadrons are confined chiral symmetry should be

broken. Here we demonstrate that it is not so and that it is possible to have confined but chirally symmetric hadrons at finite density and low temperature<sup>2</sup>.

There exists only one known manifestly chirally-symmetric and confining model in four dimensions that is solvable<sup>3</sup>. This model can be considered as a generalization of the 1+1 dimensional 't Hooft model, that is QCD in the large  $N_c$  limit. Once the gauge is properly chosen in 1+1 dimensions the Coulomb interaction becomes a linear confining potential. Then this potential properly represents gluonic degrees of freedom in 1+1 dimensions. It is postulated that there exists a linear confining potential of the Coulomb type in four dimensions either. This model represents a simplification of large  $N_c$  QCD in four dimensions. The model is exactly solvable.

**2. Chiral symmetry breaking in the vacuum.** Consider first chiral symmetry breaking in the vacuum. The Dirac operator for the dressed quark is

$$D(p_0, \vec{p}) = iS^{-1}(p_0, \vec{p}) = D_0(p_0, \vec{p}) - \Sigma(p_0, \vec{p}), \quad (1)$$

where  $D_0$  is the bare Dirac operator. Parametrising the self-energy operator in the form

$$\Sigma(\vec{p}) = A_p + (\vec{\gamma}\hat{\vec{p}})[B_p - p], \quad (2)$$

where functions  $A_p$  and  $B_p$  are yet to be found, the Schwinger-Dyson equation for the self-energy operator in the rainbow approximation, which is valid in the large  $N_c$  limit for the instantaneous interaction, is reduced to the nonlinear gap equation for the chiral angle  $\varphi_p$ ,

$$A_p \cos \varphi_p - B_p \sin \varphi_p = 0, \quad (3)$$

where

$$A_p = \frac{1}{2} \int \frac{d^3k}{(2\pi)^3} V(\vec{p} - \vec{k}) \sin \varphi_k, \quad (4)$$

$$B_p = p + \frac{1}{2} \int \frac{d^3k}{(2\pi)^3} (\hat{\vec{p}}\hat{\vec{k}}) V(\vec{p} - \vec{k}) \cos \varphi_k. \quad (5)$$

Here  $V(\vec{p})$  is the Fourier transform of the linear confining potential with the string tension  $\sigma$  with a proper infrared regularisation. The functions  $A_p, B_p$ , i.e. the quark self-energy, are divergent in the infrared limit, which implies that the single quark cannot be observed and the system is confined. However, the infrared divergence cancels exactly in the gap equation so this equation can be solved directly in the infrared limit. The chiral symmetry breaking is signalled by the nonzero quark condensate and by the dynamical momentum-dependent mass of quarks

$$\langle \bar{q}q \rangle = -\frac{N_C}{\pi^2} \int_0^\infty dp p^2 \sin \varphi_p, \quad M(p) = p \tan \varphi_p. \quad (6)$$

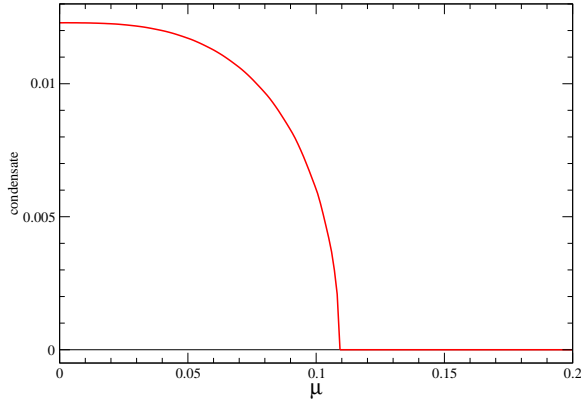


Fig. 1. Quark condensate in units of  $\sigma^{3/2}$  as a function of the chemical potential, which is in units of  $\sqrt{\sigma}$

The dynamical mass is finite at small momenta and vanishes at large momenta. Both these quantities were first obtained in ref. <sup>4</sup> and repeatedly reconfirmed in all subsequent works on this model. The numerical value of the quark condensate is  $\langle \bar{q}q \rangle = (-0.231\sqrt{\sigma})^3$ .

**3. Chiral symmetry restoration and meson spectra.** Now we are in position to include into this model a finite quark chemical potential  $\mu$  at zero temperature. Denoting the Fermi momentum of quarks as  $p_f$  one has to remove from the integration in the gap equation all quark momenta below  $p_f$  since they are Pauli-blocked. This is similar to what is done within the NJL type models or within the 't Hooft model <sup>5</sup>. At the critical quark chemical potential one observes a chiral restoration phase transition, as depicted in Fig. 1.

What crucially distinguishes this model from the NJL model is that the system is still confined, even in the chirally restored phase. This is because the self-energy integral  $B_p$  is still infrared-divergent, even when the chiral angle  $\varphi_p$  and dynamical mass  $M(p)$  identically vanish. Hence the single quark is removed from the spectrum at any chemical potential.

To demonstrate this explicitly one has to solve the Bethe-Salpeter equation for the quark-antiquark bound states applying the quark Green function obtained from the gap equation. The infrared divergence of the single-quark Green function cancels exactly in the color-singlet quark-antiquark system <sup>6</sup> and the bound state mesons are finite and well defined quantities. The spectrum below the critical chemical potential is similar to the one previously obtained in the vacuum <sup>6</sup>. The spectrum exhibits approximate restoration of the chiral symmetry in excited hadrons, for details we refer to <sup>6</sup> and for a review to ref. <sup>7</sup>.

The spectrum above the critical chemical potential, i.e. for  $\mu = 0.2\sqrt{\sigma}$ , is shown in Fig. 2. This spectrum is qualitatively different. All the states are in *exact* chiral multiplets. Though the chiral symmetry is manifestly restored in the vacuum, one

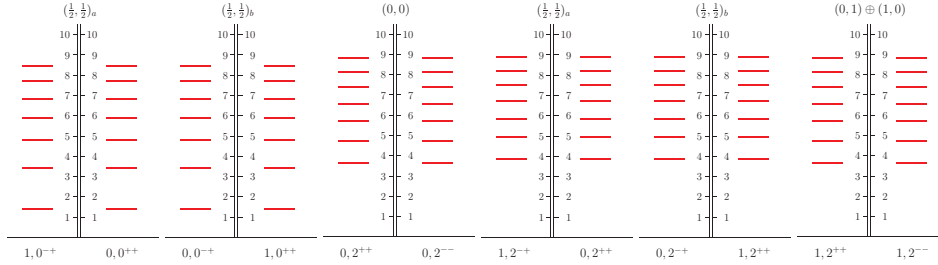
4 *L. Ya. Glozman and R. F. Wagenbrunn*

Fig. 2.  $\mu = 0.2\sqrt{\sigma}$ . Spectra for chemical potential  $\mu = 0.2\sqrt{\sigma}$ . For  $J = 0$  only the two  $(\frac{1}{2}, \frac{1}{2})$  multiplets are present (left two panels). For  $J > 0$  there are also the  $(0, 0)$  and  $(0, 1) \oplus (1, 0)$  multiplets. In the remaining four panels we show all multiplets for  $J = 2$ . Masses are in units of  $\sqrt{\sigma}$ . Meson quantum numbers are  $I, J^{PC}$ .

observes *finite-energy well defined hadrons*. Obviously the mass generation mechanism in these hadrons has nothing to do with the chiral symmetry breaking in the vacuum and is not related with the quark condensate. The mass generation mechanism for these chirally symmetric hadrons is similar to the high-lying states in the chiral symmetry broken phase.

**3. Conclusions.** We have demonstrated that it is possible to have a confining but chirally symmetric matter consisting of chirally symmetric hadrons at finite density. Whether such a chirally symmetric but confining phase exists in QCD or not is still an open question, but if it does, then it will imply dramatic modifications of the QCD phase diagram. It will also have significant implications for astrophysics: The interactions of these chirally-symmetric hadrons can be only of short-range as they decouple from the Goldstone bosons and their weak decay rate is quite different since their axial charge vanishes<sup>8</sup>.

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